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LOAPEX: The Long-Range Ocean Acoustic Propagation EXperiment

James A. Mercer, John A. Colosi, Bruce M. Howe, Matthew A. Dzieciuch, Ralph Stephen, and Peter F. Worcester

***Abstract*—This paper provides an overview of the experimental goals and methods of the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX), which took place in the northeast Pacific Ocean between September 10, 2004 and October 10, 2004. This experiment was designed to address a number of unresolved issues in long-range, deep-water acoustic propagation including the effect of ocean fluctuations such as internal waves on acoustic signal coherence, and the scattering of low-frequency sound, in particular, scattering into the deep acoustic shadow zone. Broadband acoustic transmissions centered near 75 Hz were made from various depths to a pair of vertical hydrophone arrays covering 3500 m of the water column, and to several bottom-mounted horizontal line arrays distributed throughout the northeast Pacific Ocean Basin. Path lengths varied from 50 km to several megameters. Beamformed receptions on the horizontal arrays contained 10–20-ms tidal signals, in agreement with a tidal model. Fifteen consecutive receptions on one of the vertical line arrays with a source range of 3200 km showed the potential for incoherent averaging. Finally, shadow zone receptions were observed on an ocean bottom seismometer at a depth of 5000 m from a source at 3200–250-km range.**

***Index Terms*—Acoustic scattering, acoustic tomography, coherence, low frequency, propagation, underwater acoustics.**

I. Introduction

The Long-range Ocean Acoustic Propagation EXperiment (LOAPEX) took place in the northeast Pacific Ocean between September 10, 2004 and October 10, 2004. This experiment was designed to address unresolved issues in long-range, deep-water acoustic propagation that were identified at a 1998 Office of Naval Research (ONR) workshop at Lake Arrowhead, CA [1]. These issues included: 1) the unexpected phase stability of long-range acoustic signals, 2) the evolution of space-time signal coherence with range (distance), 3) the acoustic scattering physics responsible for the vertical extension of acoustic energy far into the geometric shadow zones beneath caustics (shadow zone arrivals) [2], and 4) the effects of bottom interaction near bottom-mounted sources and receivers [3], [4]. In addition, the distribution of acoustic source and receiver locations available during LOAPEX constitute an example of moving ship tomography [5], making it possible to infer a thermographic "snapshot" of the northeast Pacific Ocean Basin at the time of the experiment.

LOAPEX was one of three closely coordinated, jointly designed ONR experiments collectively called the North Pacific Acoustic Laboratory 2004 (NPAL04): LOAPEX, led by J. Mercer of the Applied Physics Laboratory, University of Washington (APL-UW, Seattle, WA); BASSEX (Basin Acoustic Seamount Scattering EXperiment), led by A. Baggeroer of the Massachusetts Institute of Technology (MIT, Cambridge, MA); and SPICEX (SPICE EXperiment), led by P. Worcester of the Scripps Institution of Oceanography (SIO, University of California, La Jolla, CA). BASSEX used a towed horizontal receiving array to study the effects of seamounts on long-range acoustic propagation. SPICEX used 250-Hz transmissions and fixed ranges of 500 and 1000 km to: 1) elucidate the relative roles of internal waves, ocean spice (buoyancy compensated water masses with sound speeds different than the surrounding water masses), and internal tides in causing acoustic fluctuations; 2) understand the acoustic scattering into the geometric shadow zone beneath caustics (shadow-zone arrivals); and 3) explore in a limited way the range dependence of the fluctuation statistics [6]. SPICEX and LOAPEX complement one another by providing information on the frequency dependence of the scattering. BASSEX utilized transmissions from both LOAPEX and SPICEX, while LOAPEX utilized two vertical line hydrophone arrays (VLAs) installed by SPICEX.

There have been a number of well-controlled, long-range propagation experiments, e.g., SLICE89 [7]–[9], the Acoustic Thermometry of Ocean Climate (ATOC) Acoustic Engineering Test [10], the Alternate Source Test (AST) [11], [12], and the 1998–1999 North Pacific Acoustic Laboratory experiment (NPAL98) [13]. None had been designed to examine, however, the detailed range dependence of coherence and scattering as LOAPEX. Section II provides a description of the LOAPEX experiment design, the acoustic assets that were deployed, and the engineering methodologies. Section III presents examples of the data and concluding remarks are given in Section IV.

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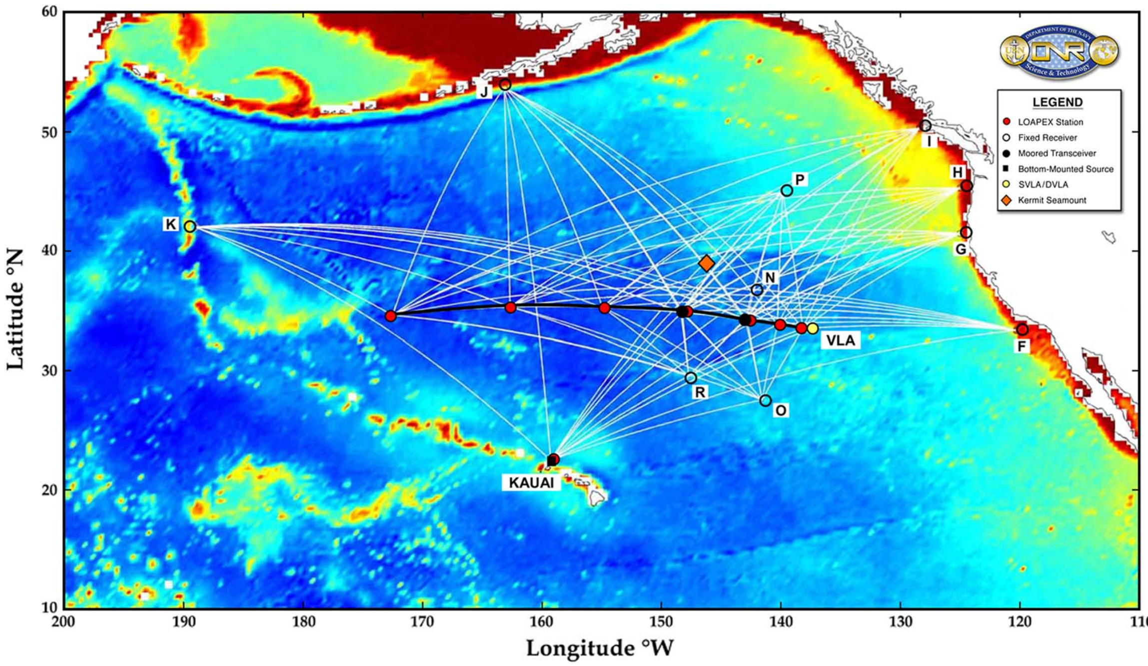

Fig. 1. Geographical locations of the various assets deployed during LOAPEX.

II. Experiment Design, Acoustic Assets, and Methods

A. Overview

The primary science objective for this experiment was to better understand how ocean sound-speed fluctuations (e.g., due to internal waves and spice) affect space-time signal coherence as a function of range and depth. An important emphasis for this experiment was to obtain a better understanding of the physics responsible for the previously observed "deep shadow zone" arrivals—long-range acoustic signals that appear with the same travel times as the deterministic lower turning point caustics, but at significantly greater depths [2], [14]. An important and related problem is the extension of the finale caustic at the end of the reception when the source is significantly off the sound channel axis. This requires an experimental configuration that includes a water-column-spanning VLA and source that could be positioned at multiple ranges and depths. This drove the design to a ship-suspended source that occupied stations at distances from a VLA ranging from kilometers to megameters. A path was chosen in the North Pacific that was a geodesic removed from strong fronts (e.g., the California Current system) and significant bathymetry. At the same time, given the in-place cabled assets of NPAL (a bottom-mounted acoustic source near the Hawaiian island of Kauai and horizontal line array receivers around the basin), we could address two additional topics: the effects of bottom interaction near bottom-mounted sources and receivers [3], [4], and a demonstration of a thermographic "snapshot" of the northeast Pacific Ocean Basin.

The geographical locations of the various assets employed during LOAPEX are illustrated in Fig. 1. The red dots indicate the eight stations at which the acoustic source was suspended from the *R/V Melville*. Approximately 24–48 h were spent at each station. Seven of these stations are on the main LOAPEX path shown as the solid black line. These seven stations were nominally 50, 250, 500, 1000, 1600, 2300, and 3200 km from a pair of VLA acoustic receivers shown as a single yellow dot (see Table I for precise locations). The VLAs were separated by only 5 km. The eighth transmission station was near the bottom-mounted acoustic source on the northern slope of Kauai. This source is cabled to a shore facility and is remotely controlled by APL-UW from Seattle, WA. The open circles labeled with single alphabetic characters indicate the approximate locations of bottom-mounted horizontal line array receivers. These fixed receivers are also controlled from APL-UW. The red diamond shows the location of the Kermit Seamount about which BASSEX data were collected, and finally, the two black dots 500 and 1000 km from the VLA receivers on the main LOAPEX path indicate the locations of two moorings with 250-Hz acoustic transceivers that were installed for SPICEX. Not shown on this figure are the locations of four ocean bottom seismometer/hydrophone (OBS/H) packages deployed around the deeper of the two VLAs (see Fig. 7).

B. The Acoustic Sources

The acoustic source that was suspended from the *R/V Melville* (Fig. 2) is identical to the bottom-mounted source near Kauai. Both were purchased for the Acoustic Thermometry of Ocean Climate (ATOC) project [15] and were made-to-order by Alliant Techsystems, Inc. (Mukilteo, WA, now out of business) [16]. The source design is based upon the proven barrel-stave bender-bar transduction design. When deployed to a specific depth, the internal cavity of the "barrel" is filled with gas to the ambient pressure to provide the necessary compliance for efficient performance. At each LOAPEX station, the source was initially deployed to the deepest depth planned for that station. For the first few stations this was 800 m. Once the source had reached the desired depth, an acoustic signal from a small transducer suspended near the surface activated an acoustic valve

TABLE I
STATION COORDINATES, WITH NOMINAL RANGE TO THE DEEP VLA

Station	Latitude	Longitude	Latitude N		Longitude E		Distance to DVLA
	dec deg N	dec deg E	deg	min	deg	min	km
DVLA	33.418920	-137.682470	33	25.135	-137	40.948	0
SVLA	33.418400	-137.740930	33	25.104	-137	44.456	5
T50	33.513590	-138.208350	33	30.8154	-138	12.5010	50
T250	33.869780	-140.322990	33	52.1868	-140	19.3794	250
T500	34.248840	-142.882500	34	14.9304	-142	52.9500	490
T1000	34.864170	-148.280130	34	51.8502	-148	16.8078	990
T1600	35.285610	-154.949970	35	17.1366	-154	56.9982	1600
T2300	35.312730	-162.647970	35	18.7638	-162	38.8782	2300
T3200	34.631820	-172.472870	34	37.9092	-172	28.3722	3200
kauai	22.553691	-159.249620	22	33.2215	-159	14.9772	2432

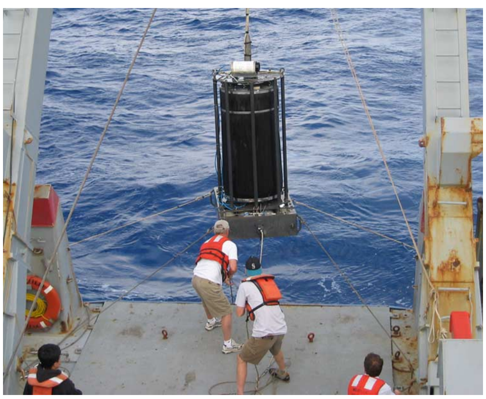

Fig. 2. Acoustic source being deployed from the fantail of the *R/V Melville*.

Fig. 3. Source deployment winch with 1.7-cm cable (standard 0.68-in oceanographic cable), and one of two air compressors, all mounted in one half of a 20-ft van. The other half of the van housed the power amplifier, signal generation electronics, and a computer.

mounted on the source. The valve released the gas stored in four high-pressure (41.37 MPa, 6000 lbf/in^2) bottles mounted in a frame underneath the source. As the gas was released into the cavity, the impedance of the source was monitored via the signal cable until it ceased to change measurably. This was the indication that the internal pressure had reached the ambient level. The gas valve was then closed by another acoustic signal from the ship. When the source was raised to the shallow transmission depth (350 m), the excess gas voided through an open port in the bottom of the cavity. Midway in the cruise, problems with the pressurization system limited the deeper depth to 500 m. The problem was eventually traced to a gas filter and 800 m was again attained at the final station.

The source was lowered from the ship on a 1.7-cm cable (standard 0.68-in oceanographic cable) that also served as the signal cable. The purpose-built cable winch, the air compressors for refilling the gas bottles and to power the deployment "air tuggers," and lab space housing the transmit electronics were all integrated into a standard 20-ft van for portability (Fig. 3). LOAPEX acoustic signals were generated from digital files run on an 80486 PC, then converted to analog by a National Instruments (Austin, TX) digital-to-analog (D/A) converter board, and finally amplified by a 48-kVA Ling power amplifier. Transmission timing accurate to 1 μs was provided by a Spectrum Instruments (San Dimas, CA) global positioning system (GPS) receiver that also gated the triggering clock to the D/A converter.

Three different types of acoustic signals were transmitted from the suspended source during LOAPEX and all were processed by digital replica correlation (details in Section II-C4). The most frequently transmitted signal was an M-sequence (Table II). The M-sequence most often used in the experiment is a phase-modulated carrier with two cycles of the carrier frequency making 1 b of a 1023-b code. The carrier frequency of the suspended source when deployed to 800 m was 75 Hz, and 68.2 Hz when suspended to 500 or 350 m. Because the characteristic impedance of the source changed somewhat with depth, the carrier frequency was selected to optimize the transmit waveform while minimizing electrical and mechanical stresses. The choice of the 350- and 500-m depth carrier frequency involved several compromises. The requirement for a periodic waveform dictated that the waveform contain an integer number of carrier periods. In addition, the VLA receivers' (AVATOCs) schedules were preprogrammed to collect 40 M-sequences (for the 20-min transmissions) with 75-Hz carriers. M-sequences at a slightly different carrier frequency would not fit an integer number of sequences into the preprogrammed collection window. The choice of a 68.2-Hz carrier for the 350- and 500-m depths was considered an adequate compromise since at this

TABLE II
M-SEQUENCE SIGNAL PARAMETERS

Parameter	M68.2	M75	Kauai	PL350	PL800
law [octal]	2033	2033	3741	5	5
digits	1023	1023	1023	3	3
carrier [Hz]	68.2 Hz	75 Hz	75 Hz	68 Hz	75 Hz
cycles per digit	2	2	2	5	5
modulation angle [°]	88.209215	88.209215	88.209215	69.3	69.3
duration [s]	30.0000	27.2800	27.2800	0.2206	0.200

TABLE III
PRESCRIPTION FREQUENCY MODULATED (PFM) SIGNAL PARAMETERS

	PFM350	PFM800
Design depth (m)	350	800
Sweep frequency range (Hz)	32-92	45-105
Duration (s)	30.0000	30.000

carrier frequency transmitting 40 M-sequences of 1023 b with two carrier cycles per bit filled the 20-min receiver collection window. The Kauai acoustic source is on the bottom at 811 m so its carrier frequency was also 75 Hz. However, the bit code for the Kauai source is "orthogonal" [15] to that used for the suspended source. This allows receptions that overlap in time at distant receivers to be separated from one another after replica correlation. All of the transmissions from the Kauai source during LOAPEX were 20 min in duration; i.e., 44 repetitions of the 1023-b code. M-sequence transmissions from the suspended source were either 20 or 80 min in duration (44 or 176 repetitions, respectively).

The second type of transmission used on the suspended source, and only from the final station near the island of Kauai, is called a "Pentaline" transmission [17]. The Pentaline transmission is not really a different type of transmission, nor a signal with five pure tones, but rather a 3-b M-sequence whose spectrum has five distinct peaks (PL350 and PL500 in Table II) allowing a more direct analysis of the frequency-dependent phase coherence. These signals have five cycles of the carrier frequency per bit and a phase modulation of 69.3° between the "0" and "1" bits. All Pentaline transmissions were 20 min in length. The carrier frequency for 350- and 500-m depths was 68 Hz and at 800-m depth, it was 75 Hz.

A third transmission used with the suspended source is referred to as the "prescription FM" signal (Table III) [18]. These experimental signals were designed with a variable frequency sweep rate. The sweep rate was low at frequencies where the response of the source is relatively low and fast where the response is higher, providing a more equal energy density across the band and effectively broadening the bandwidth. An optimization procedure was used to maximize the source level while keeping electrical and mechanical stresses below acceptable levels. For source depths of 350 and 500 m, the sweep band was from 32 to 92 Hz (PFM350 in Table III and for the 800-m source depth, the band was from 45 to 105 Hz (PFM in Table III). For all depths, the period of the sweep was 30 s and the period was repeated 40 times to produce 20-min transmissions.

The schedule for LOAPEX transmissions was based upon a predetermined schedule that was programmed into the AVATOC data acquisition systems on the two SIO VLAs. Because the line arrays operated autonomously, the suspended source transmission times had to be adjusted based upon the station location; nevertheless, while on station transmissions were scheduled once per hour. The only exception to this occurred following the 80-min transmissions, which in fact included the time frame for the following hourly scheduled 20-min transmission. The 80-min transmissions were always preceded in the previous hour by a 20-min prescription FM transmission. The Pentaline transmissions were only used at the station near Kauai, where two of them were inserted in the hours before the prescription FM transmissions. Fig. 4 provides a schematic history of the suspended source transmissions during LOAPEX. In this figure, the vertical axis is time in year-days from January 1, 2004 (note that 2004 was a leap year). The labels T50, T250, etc., refer to the various transmission stations illustrated in Fig. 1 and to their approximate distances in kilometers from the deeper of the two VLAs. "TKauai" is the suspended source station near the island of Kauai. The increasing period of time in year-days between stations is due to the increasing distance between the stations (requiring more transit time) and because more time was spent transmitting from the more distant stations. The horizontal scale is the UTC time in hours and the various characters indicate the type and length of the transmission and the depth of the suspended source. It is clear that 20-min M-sequences (smaller "M" in Fig. 4) were by far the predominant transmissions. All together, there were 228 transmissions totaling nearly 100 h during LOAPEX.

All LOAPEX transmissions were preceded by a ramp-up to full power. This precursor is not included in the previously stated transmission durations. The ramp-up started 5 min plus one period (e.g., 300 s + 27.28000 s = 327.2800 s for the 75-Hz signal M-sequence signal) before the prescribed start time of the transmission at a level of 0.26 W (165 dB re 1 μPa @ 1 m) and increased in level 6 dB every minute until the desired output level was reached. The ramp-up was intended to alert marine life close to the source, and allow sufficient time for an animal to increase its distance from the source. All acoustic transmissions were made at a nominal level of 260 W or 195 dB re 1 μPa @ 1 m. These levels were verified by receptions on a calibrated hydrophone suspended from the ship. A full description of the planned transmission signals and the duty cycles were included in an environmental assessment that led to the approval for LOAPEX.

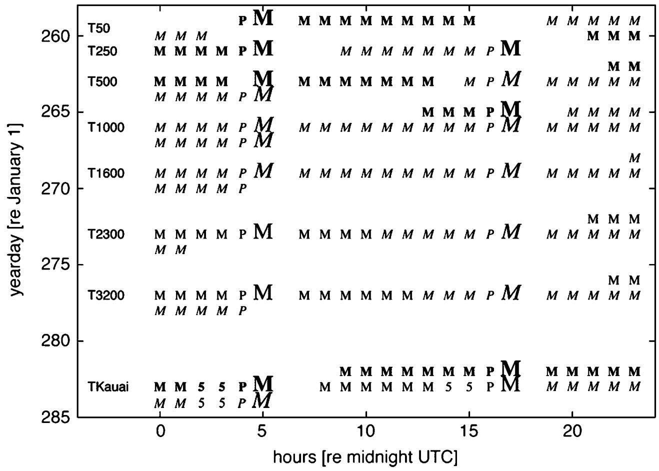

Fig. 4. Schematic history of the suspended source transmissions during LOAPEX. The transmitted signals are given as follows: "M" is an M-sequence, "P" is a prescription FM, and "5" is a Pentaline transmission. The transmitter depth is indicated by the type of font: 350-m depths are in italics, 500-m depths are in roman, and 800-m depths are bold roman. The length of the transmission is shown by the font size: 20-min transmissions are the smaller size and 80-min transmissions are the larger size. (Note that 2004 was a leap year.)

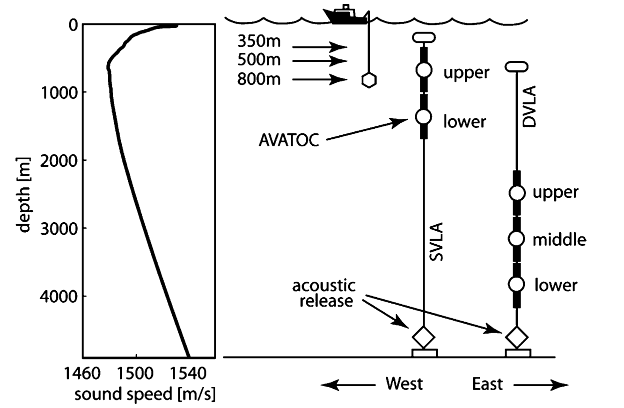

Fig. 5. Depths of the five VLA sections, the suspended source depths, and a typical sound-speed profile.

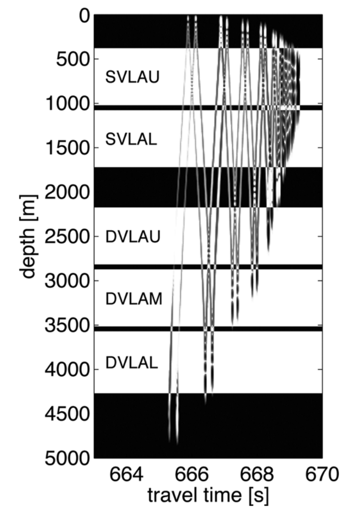

Fig. 6. Intended coverage depths of the five SIO VLA subsections are indicated by the white regions of the figure. Each region is labeled; for example, SVLAU means shallow VLA upper subsection. A predicted time front from transmit station T1000, generated by a modified Monterey–Miami Parabolic Equation (MMPE) code, is overlaid to indicate the intended coverage of the VLA subsections. The time front was computed without including scattering phenomena. Although the DVLAM subsection was inoperative, the scattered extension of the third arriving pair of deep cusps should be observable in the DVLAL subsection.

C. The Acoustic Receivers

1) The Vertical Line Arrays: The VLAs were installed by the SIO and their locations are represented by a single yellow dot in Fig. 1; exact coordinates of their anchors are given in Table I. Fig. 5 provides an illustration of the VLAs. Because of the combined weight of the acoustic arrays, it was necessary to deploy two separate moorings. The shallow VLA (SVLA) was located 5 km due west of the deep VLA (DVLA). The DVLA consisted of three acoustic subsections, upper, middle, and lower, each containing a 20-element array with nominal 35-m spacing between hydrophones. The total length of the DVLA was 2100 m, and it extended from a nominal depth of 2150 down to 4270 m, with one 20-m gap for floatation. The SVLA consisted of two sections, upper and lower, also each containing a 20-element array with nominal 35-m hydrophone spacing. The total length of the SVLA was 1400 m, and it extended from a nominal depth of 350 m down to 1750 m. The SVLA was positioned about the sound channel axis to optimize resolution of acoustic modes 1–10 at 75 Hz. The DVLA was positioned to span many of the lower caustics in the predicted time-front arrival pattern as illustrated in Fig. 6. The positions of both VLAs were tracked with a surveyed set of six bottom-mounted acoustic transponders that were interrogated by transducers mounted on the arrays. The offsets of the rubidium/crystal internal clocks associated with each array section were determined following the recovery of the arrays and subsequent corrections provided acoustic arrival times accurate to 1 ms in absolute time. Unfortunately, all of the data from the middle section of the DVLA were lost due to a water leak into its pressure case.

2) The Bottom-Mounted Hydrophone Arrays: The approximate locations of the bottom-mounted horizontal hydrophone arrays are shown as open circles in Fig. 1. All of these arrays have an undersea cable to shore, and their receivers are autonomous with remote command and control from APL-UW. Accurate timing was provided by TrueTime GPS receivers at the microsecond level. The acoustic receivers were remotely scheduled to "turn on" just before the receptions from the suspended source. In addition, just as they have for almost ten years, the receivers were scheduled to receive the Kauai bottom-mounted source transmissions and periodic samples of ambient noise.

3) Ocean Bottom Seismometer/Hydrophone Assemblies: The idea to deploy OBS/Hs for LOAPEX originated at a APL-UW/WHOI workshop [19]. Four OBS/H units each containing a vertical geophone and a hydrophone were deployed to the ocean bottom at about 5000 m in a 4-km square pattern about the DVLA (Fig. 7). Even though the critical depth, the deepest depth predicted for purely refracted acoustic arrivals by deterministic models, was roughly 4200 m, the OBS/H packages at 5000 m received the LOAPEX transmissions.

4) Signal Processing: In general, signal processing for all receptions is based upon replica correlation. The first step is sequence summing in which L consecutive sequences, the stan-

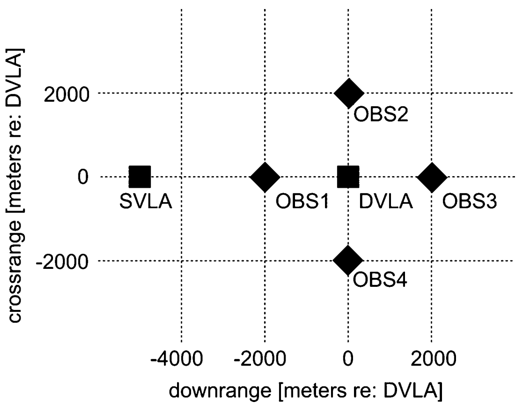

Fig. 7. Deployment locations of four OBS/hydrophone assemblies near the DVLA and the SVLA.

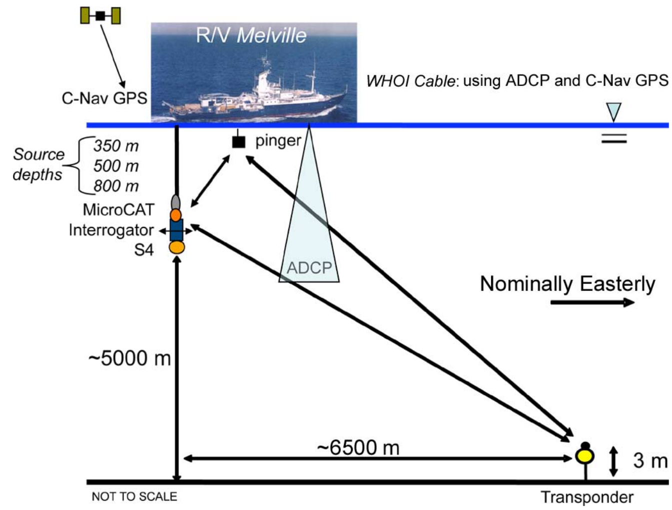

Fig. 8. Source location and velocity were determined from a numerical dynamic cable model forced by data from a C-Nav GPS receiver and the ship's ADCP. Data from a pressure sensor, current meter, and an acoustic transponder were used to verify the model output.

dard M-sequences, for example, are added together coherently in the time domain. To optimize processing, L is based on the coherence time of the received signal and the resulting processing gain is $10\log(L)$. The second step is beam forming. If the signal is coherent across the array and the noise is isotropic, the array gain is $10\log(M)$, where M is the number of hydrophone elements in the array. The next step is pulse compression in which the recorded data are complex demodulated and correlated with a stored replica of the transmission. This process produces a triangular-shaped pulse with a time resolution of 1-b length, or 27 ms, and additional processing gain of $10\log(N)$, where N is the number of bits in the sequence. As a final step, individual coherent results can be grouped and summed incoherently.

The processing described above assumes that the signal coherence time is a known quantity, where in reality determining coherence time was a principle goal of the experiment. Two primary factors determine the received coherence time: 1) the magnitude and extent of variability in the intervening ocean; and 2) the motion of the source and the receiver. The first item is determined by the locations of the source and receivers. Source and receiver motion is not an issue for the bottom-mounted source near Kauai and receptions on the bottom-mounted horizontal hydrophone arrays or the OBSs, but it is an issue for the suspended source and the VLAs. To better understand this issue, a Doppler simulation study for the suspended source and VLA receiver was completed. Simulated source motions of a few meters per 20 min and VLA hydrophone motions of hundreds of meters per M2 tidal cycle were used. The resulting de-coherence due to motion was compared to that resulting from internal waves with a Garret–Munk spectrum (GM) strength equal to one. The LOAPEX study concludes: 1) Doppler-induced intensity fluctuations are a few tenths of a decibel, rarely more than 0.5 dB; 2) Doppler-induced travel time fluctuations are a few milliseconds, rarely more than 5 ms (cf., 1 b of a 75-Hz M-sequence is 26.7 ms); and 3) Doppler processing is necessary for coherence studies to separate incoherence due to source–receiver motion from that due to ocean variability. Section II-D describes the effort to track the positions and velocities of the suspended source and the VLA hydrophones.

D. Source and Receiver Navigation

1) Source Navigation: A significant effort was made to collect data that would allow the precise determination and verification of the suspended source location and velocity during transmissions. The thermographic snapshot of the ocean requires precise source localization and the estimates of signal coherence require precise determination of source velocities. Although the *R/V Melville* maintained a relatively constant position at each station using its dynamic positioning system, the great depths to which the acoustic source was deployed required a novel approach for source position and velocity measurements. Fig. 8 provides an illustration of the various navigation instruments that were used. A goal was set to measure the absolute source position at 1-s intervals to one-tenth of the acoustic wavelength, or about 2 m, and relative velocities to 0.2 cm/s. The primary method of achieving this goal was to apply a numerical finite-difference dynamic cable prediction model [20]. In addition to the static input parameters listed in Table IV, the model forcing data consisted of the 3-D position of the source suspension point on the *R/V Melville's* A-frame as determined by a C-Nav GPS (C-Nav GPS is marketed by C&C Technologies, Lafayette, LA), and the water current profile as determined by an RDI (Poway, CA) acoustic Doppler current profiler (ADCP).

The C-Nav GPS package provides dual-frequency worldwide corrected position and velocity estimates. The dual frequency corrects for ionospheric errors, while data from globally distributed ground stations are used to correct for GPS satellite ephemeris errors, GPS clock error, and other atmospheric effects in real time via a geostationary satellite downlink. The C-Nav data were generally very good during the experiment. When the number of available GPS satellites “in view” dropped below five, some outliers were observed, but this occurred less than 2% of the time; when it did occur, the duration was less than the time constant of the suspended source pendulum motion so that the errors were easily addressed.

The C-Nav system was reported to have decimeter accuracy and this was verified, at least while the ship was at the pier in the San Diego harbor. However, to provide validation of the position data and model output while at sea, additional measurements were acquired. As the *R/V Melville* approached each of the transmit stations (approximately 5 km before) an acoustic transponder was dropped to the ocean floor. Once the LOAPEX source was deployed, interrogations from an acoustic transmitter attached to the cable 6 m above the 75-Hz acoustic source provided a 1-D comparison along the acoustic path to the VLAs (approximately east–west) of the source position with the output of the dynamic cable model. Even though transponder receptions were relatively noisy, the root mean square difference between the transponder data and the dynamic cable model estimate of position in the east–west direction ranged between 0.6 and 2.2 m.

A Seabird MicroCAT (Sea-Bird Electronics, Inc., Bellevue, WA) was attached to the cable 20 m above the source to measure depth (pressure) and to allow a comparison with the vertical position estimated by the dynamic cable model. Because the MicroCAT logged 6-s depth averages every 15 s (not the ideal sampling for a nominal 10-s surface wave/ship heave period) a direct comparison with the 1-s output from the dynamic cable model was problematic. However, the results of the comparison never appeared inconsistent. For example, the cable model output for station T250 while the source was at a depth of 800 m showed typical variations in depth of roughly 1 m with a few excursions of 2 m. The data logged by the MicroCAT followed the same pattern except the amplitudes were approximately 60% of that predicted by the model, which is what one would expect given the low sample rate of the MicroCAT.

The ship's ADCP was able to make 3-D current estimates down to 800 m, the deepest of the source deployment depths. Absolute current measurements were obtained by removing the ship motion as determined by the ship's Ashtech P-code GPS. ADCP depth bins of 16 m were averaged over 5-min intervals to reduce measurement uncertainty and random errors. Finally, an InterOcean Systems S4 current meter (InterOcean Systems, Inc., San Diego, CA) was installed on the cable 6 m below the acoustic source to measure the 3-D velocity of the water relative to the source. By combining these data with the ADCP velocities at the nominal source depth, an estimate of the absolute velocity of the source was obtained for comparison with the dynamic cable model. Again, sampling mismatches were a minor problem. The ADCP was averaged over 5 min and the S4 provided data at 30-s intervals. Nevertheless, the comparisons were rather good. Fig. 9 provides a comparison of the east–west velocities as estimated by the dynamic cable model and the ADCP/S4 method while at a depth of 800 m at station T250. Detailed analysis of the source motion is the subject of a thesis by Zarnetske [21].

2) VLA Navigation: The VLAs shared one transponder net made up of six transponders. Each of the VLA sections (two in the SVLA and three in the DVLA) had an electronics package that was capable of interrogating the transponder net. The interrogators transmitted once per hour, but sequentially so that a total of 400 s was required for all five of them to transmit. The six transponder replies from all five interrogators were received on each interrogator and on six hydrophones within each 20-element array section. Because of the depth of the VLAs, the high tension in the array cables, and the lack of a surface forcing component, the motion of the VLAs was relatively slow and corresponded primarily to the tidal forcing. Fig. 10 provides an example of the DVLA navigation. Note the exaggerated appearance of tilt due to the axes' values. Data for the middle section of the DVLA were lost due to a water leak into the electronics pressure case. Positions for the remaining 14 of the 20 hydrophone elements in each section were interpolated from the six hydrophone interrogator receptions within the section. Due to infrequent VLA navigation during the LOAPEX transmissions, it has proven difficult to position the VLA hydrophones with an accuracy better than 5 m. Many analytical techniques were employed including the incorporation of a tidal model but improvement was not possible. This will limit the eventual conclusions regarding coherence.

E. Environmental Measurements

Environmental data were collected during LOAPEX to support the eventual acoustic numerical modeling effort and the resulting comparisons with actual acoustic data. At each of the eight acoustic stations, a full-ocean-depth conductivity–temperature–depth (CTD) profile was taken. As the *R/V Melville* transited between each of the stations from T50 to T2300, an underway CTD (UCTD) [22] was deployed. This novel device consists of a CTD probe that was dropped off the fantail as the ship transited; as it fell, a Kevlar line spooled off from a reel on the fantail and from a spool in the probe. The double spooling allowed the probe to fall freely until all of the line was removed from the spool in the probe. Typical depths achieved while transiting at 6.2–6.7 m s^{-1} were 300–400 m. When all of the line was spooled off the probe, the probe was reeled in on a powered reel and taken into the lab for data transfer. As the data were being transferred the probe spool was rewound and made ready for another deployment. A total of 156 UCTD casts were completed at approximately 15-km intervals. Two UCTD probes were available to us, and after losing one probe due to fraying of the lowering line, we stopped the UCTD operation after 2300 km for fear of losing the last probe. The UCTD probes were calibrated before and after the cruise.

During the transit intervals in which UCTD casts were made, expendable bathythermograph (XBT) drops were made at 50 km intervals, and after the UCTD casts were terminated, the distance between XBT drops was reduced to 25 km. ADCP measurements and bathymetric measurements with the ship's multibeam sonar were made at all times during transit.

Another novel measurement approach was the use of autonomous vehicles to collect CTD data. In this case, two Seagliders [23] manufactured at the APL-UW, were deployed near station T50. These vehicles are not powered by a propeller, but rather by buoyancy control; a hydraulic system moves oil in and out of an external bladder to force the glider up or down through the ocean. In addition, the location of the glider's battery pack can be adjusted to cause the glider's nose to pitch up or down, or to roll its wings to change compass heading. The LOAPEX Seagliders measured temperature, pressure, salinity, oxygen, and RAFOS long-range acoustic navigation

TABLE IV
INPUT DATA FOR THE NUMERICAL DYNAMIC CABLE MODEL

Ship/Platform	
ADCP Profiles	Time series
GPS position (C-Nav)	Time series (converted to velocity by model)
Cylindrical Source	
Diameter	1.1 m
Height	2 m
Buoyancy	5976 N
Mass	2409 kg
UNOLS 0.680" Cable	
Horizontal Drag coefficient	1.5
Vertical drag coefficient	0.01
Bulk modulus	11.1 MPa
Diameter	17 mm
Wet mass	8.1 kg/m
Static Elongation	1.6 m (800 m with 2400 kg)
Medium (Seawater)	
Density	1025 kg/m^3
Gravity	9.81 m/s^2

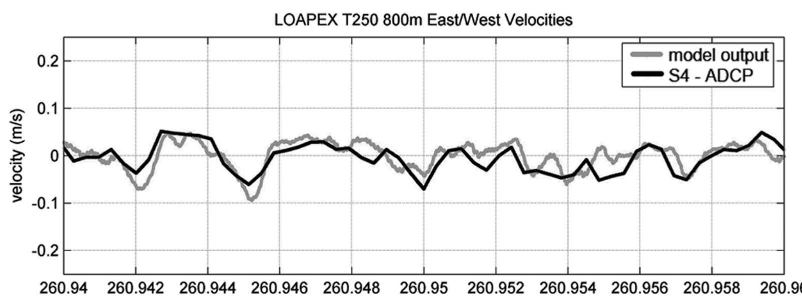

Fig. 9. Comparison of the suspended source velocity in the east–west direction as determined by the dynamic cable model and the S4 current meter combined with the ADCP. Note: the horizontal scale is in year-days from January 1, 2004 but represents only about 30 min of time during a transmission from site T250.

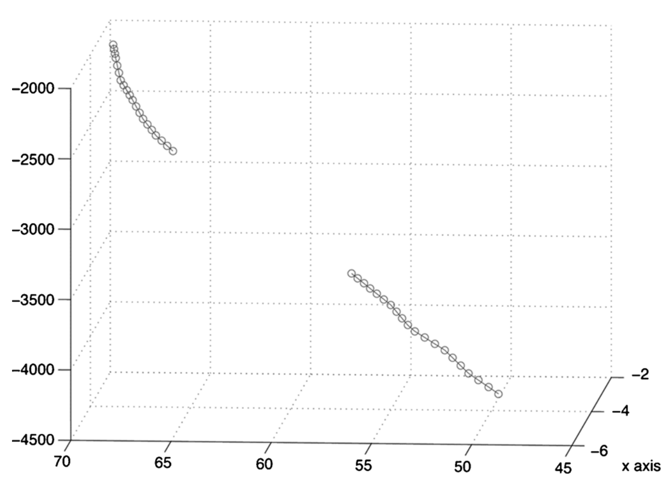

Fig. 10. Example of acoustic navigation of the DVLA. All three axes are in meters, but the scale change exaggerates the apparent tilt of the arrays. The middle section is missing due to a leak in the electronics case.

data while traveling about 3000 km, and making approximately 600 dives to a depth of 1000 m. The Seagliders contacted a pilot at APL-UW by Iridium modem each time they surfaced, so their position, status, and data were available in near real time. From T50, the first Seaglider was directed back to the DVLA before returning on the main LOAPEX path to station T1000 where it was turned toward the island of Kauai. The second Seaglider was directed to intersect the path between the DVLA and the Kauai acoustic source. Once this path was intersected, it followed the path to Kauai. After 191 days at sea, the Seagliders were finally steered to the leeward side of Kauai for pickup on March 24, 2005. Fig. 11 illustrates the paths of the two Seagliders along the specified acoustic transmission paths during their record setting deployment.

III. ACOUSTIC DATA SAMPLES

A. Bottom-Mounted Hydrophone Array

Section II-C4 described the basic steps in signal processing. The data example shown in Fig. 12 is a beamformed reception on the bottom-mounted horizontal array indicated by the letter "R" in Fig. 1. This array is at a depth of 1309 m. The suspended source transmitter was located at station T250; the source–receiver range was 848.571 km. In this example, the coherence time has not yet been determined so the processed reception includes only one of the 27.28-s M-sequences. In addition, the source and receiver motions have not yet been removed. The vertical axis is the usual conical arrival angle associated with horizontal line arrays. Because the array is not normal to the

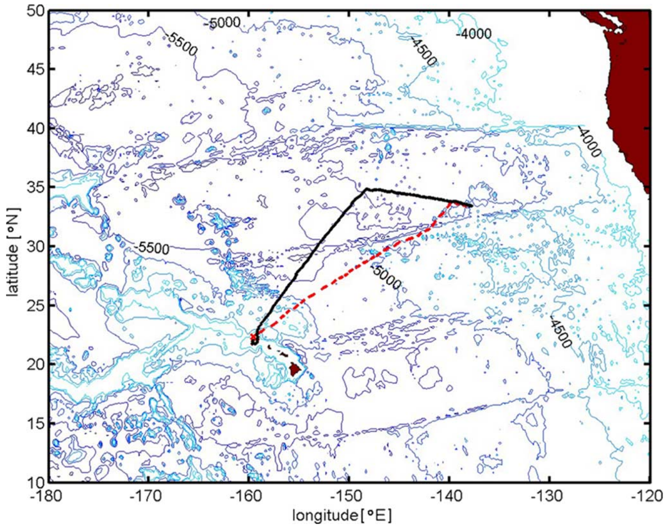

Fig. 11. Paths of the two LOAPEX Seagliders from their deployment at T50 to Kauai where they were recovered after nearly 600 dives to 1000 m and a journey of approximately 3000 km over 190 days.

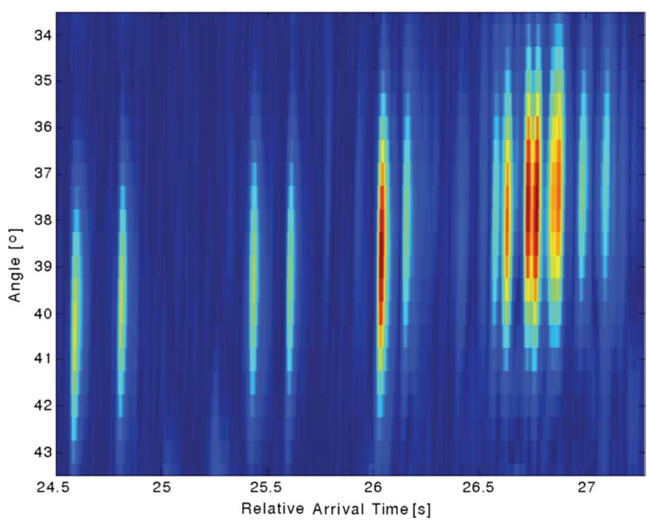

Fig. 12. Beamformed reception showing "ray-like" arrivals with relative intensities as measured on the bottom-mounted horizontal hydrophone array indicated by the letter "R" in Fig. 1. The suspended source was at station T250 and a depth of 800 m. Only one 27.28-s M-sequence was processed for this figure.

direction of propagation and because the multipaths have different vertical arrival angles, the apparent angle of arrival (the conical angle) varies during the reception. The horizontal axis is a reduced travel time window that captures several of the early "ray-like" arrivals. Consecutive processed M-sequences reveal fading in amplitude and splitting in time of deterministic ray-like arrivals (not shown).

Because the suspended source was typically transmitting every hour while on station it is possible to "stack" the receptions into a "dot plot" to better visualize the consistent arrivals. Fig. 13 is a dot plot comparing receptions on the horizontal array located at position "R" in Fig. 1, while the suspended source was located at station T50 at a depth of 800 m, and while located at station T1600 at a depth of 500 m; source–receiver ranges were 1004.399 and 926.205 km, respectively. In this

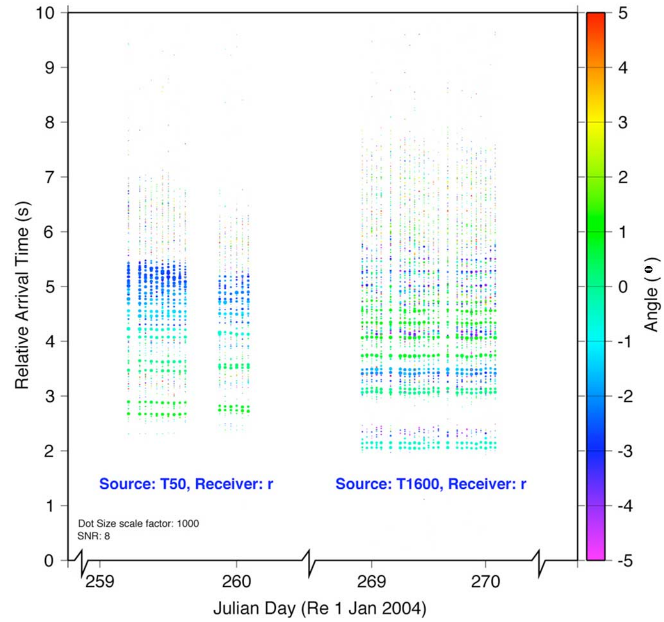

Fig. 13. Multiple receptions on the bottom array indicated by the letter "R" (Fig. 1) while the suspended source was at station T50 and station T1600. While at station T50, transmissions were made from two source depths, 800 and 350 m. The separation in time between closely arriving pairs decreases with the shallower depth. While at station T1600, the source depth was 500 m.

figure, the vertical axis is the reduced travel time window, and the horizontal axis is the year-day. A vertical line of reception dots is typically separated by 1 h from the adjacent vertical line of dots. In this presentation, the horizontal alignment of dots quickly reveals those individual acoustic path receptions that are consistent. Each dot represents the arrival time of a signal-to-noise ratio (SNR) peak after processing. The diameter of the dot indicates the SNR of the arrival. SNRs less than 8 dB were eliminated from this plot. In the earliest seconds of the reduced arrival time window, horizontal pairs of arrivals are seen. The pairs of arrivals correspond to equal, but positive and negative vertical source angles, and therefore, the ray paths experienced approximately the same average sound speed. As predicted before the experiment, these pairs arrive much closer together in time when the source is at a shallower depth as during the second group from T50 when the source depth was 350 m, and the receptions from T1600 when the source depth was 500 m.

B. Vertical Line Array

Although a portion of the VLA was lost, the data that were recorded should be very useful. Fig. 14 is an example of processed receptions on the upper 20-element subarray of the DVLA when the LOAPEX source was suspended to a depth of 350 m at a range of 3200 km. Fifteen transmissions were incoherently averaged together. In this figure, each hydrophone of the subarray was processed independently and the "accordion" time-front structure is evident. The tail of the "accordion" is not present due to the shallow source depth. There have been no corrections for source motion or VLA motion in these data. The initial effort will be to quantify fourth-moment statistics, for

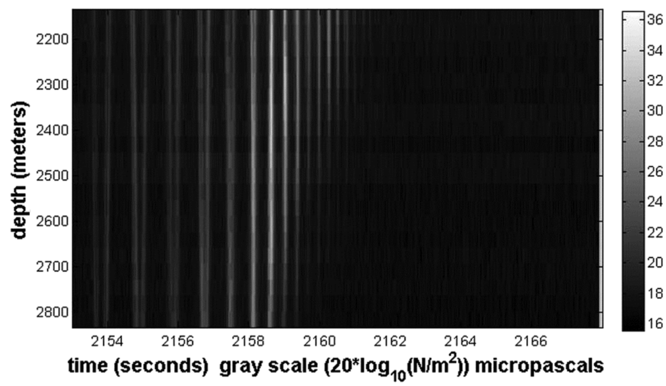

Fig. 14. Processed results for 15 separate transmissions incoherently averaged on the upper section of the DVLA showing relative intensities of a portion of the time-front while the source was at a range of 3200 km. Because the source depth of 350 m was well above the channel axis depth near 800 m, the tail of the time front is cut off. There were no corrections for source or receiver motion.

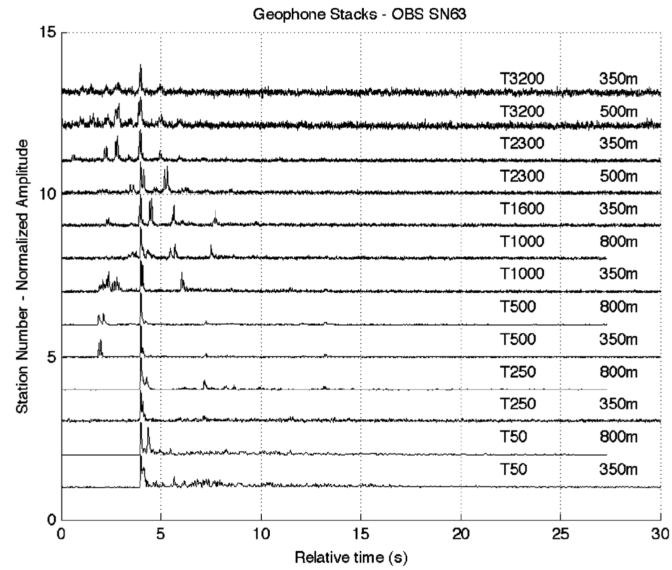

Fig. 15. Geophone (SN63) "shadow zone" receptions from all of the transmit stations along the primary LOAPEX path. At a given station, all of the M-sequences from all of the transmissions at a given depth have been "stacked" together. This geophone is at a depth of 5000 m, well below the depth at which deterministic arrivals are predicted.

example, the scintillation index, which should not be sensitive to Doppler in the acoustic data.

Once the Doppler corrections have been applied to the entire ensemble of data, analyses of time, frequency, horizontal and vertical coherence, and their range dependencies will be made. Other analyses will address the shadow zone phenomena, the effects related to the bottom near Kauai, and the thermographic snapshot.

C. OBS/Hydrophone

Four OBS/H units provided by the U.S. National Ocean Bottom Seismograph Instrument Pool were deployed about the DVLA. Fig. 15 shows geophone "shadow zone" receptions from all of the transmit stations along the primary LOAPEX path. At a given station, all of the M-sequences from all of the transmissions at a given depth have been stacked together. This geophone is at a depth of 5000 m, well below the depth at which deterministic arrivals are predicted.

D. Tidal Comparisons

One of the important initial efforts was to compare the variations in acoustic arrival times with predicted variations due to tidal motion. Although the effect is small, and in general, dependent upon the distance between the source and the receiver, the average tidal motion of the water over long distances is enough to increase or decrease the effective propagation speed and thus arrival times by a measurable amount (i.e., sound travels faster with a current than against it). For example, the predicted variation due to tidal effects between the bottom receiver "R" and the various LOAPEX stations ranged from 10 to 20 ms. If the measured arrival times agree in amplitude and phase, it is a good validation of the experimental control.

The tidal model developed by Egbert *et al.* [24] was used to develop tidal velocities over the northeast Pacific region, and software written by Dushaw [25] was applied to extract the tidal velocity components along the paths between the LOAPEX stations and the bottom-mounted hydrophone arrays. The spatial distribution of the bottom arrays provides a good basis for this comparison because they cover a broad range of azimuth angles, and as the arrays are fixed on the bottom, the problem of receiver motion is eliminated. The compensation for source motion in this analysis does not change the results because the measured travel times were averaged over a long time compared with ship

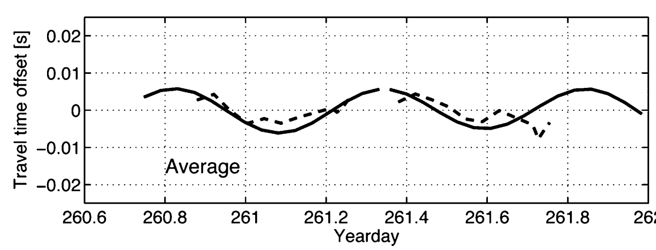

Fig. 16. Comparison of measured arrival time variations and predicted variations (based upon a tidal model) for the situation where the source was located at station T250 at a depth of 800 m and the receptions were on the horizontal array indicated by the letter "R" in Fig. 1.

motion. As an example, Fig. 16 illustrates the comparison of predicted travel time variations at receiver "R" (solid line) with those measured (dashed line) while the source was at a depth of 800 m at station T250. The dashed line represents the average arrival time of four deterministic multipaths. The comparisons in amplitude and phase are very good considering the small amplitude of the "tidal signal." Comparisons for other bottom receivers are also good and are presented by Zarnetske [21].

IV. Concluding Remarks

The LOAPEX was completed between September 10, 2004 and October 10, 2004. The experiment provides acoustic data over paths ranging from 50 km to several megameters. The acoustic source was suspended to various depths and navigated at 1-s intervals to an absolute accuracy of 2 m. A comparison of acoustic arrival time variations from transmissions at each station to bottom-mounted fixed receivers agreed very well with predicted tidal variations in both amplitude and phase validating the control in LOAPEX and the accuracy of the source navigation. Mooring motion data for the VLAs is less comprehensive but the motion is primarily tidal, so interpolations in time based upon a model should produce useful position estimates; and as a result, range-dependent coherence analysis to the VLAs should be possible. While the failure of the middle section of the SPICEX DVLA is unfortunate, the data from the other sections of the VLAs and the OBS data are adequate to support investigation of the shadow zone phenomena. Various instruments collected a large amount of environmental data to calculate sound speed, and the large number of source–receiver paths will allow a thermographic objective map of the northeastern Pacific Ocean to be constructed. Finally, it is expected that the suspended source transmissions near the island of Kauai will help answer questions about the effect that the bottom has on transmissions from the bottom-mounted Kauai acoustic source.

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Matthew A. Dzieciuch, photograph and biography not available at the time of publication.

Ralph Stephen, photograph and biography not available at the time of publication.

Peter F. Worcester, photograph and biography not available at the time of publication.